ttHH for HL-LHC

SNOWMASS EF01 8/05/20

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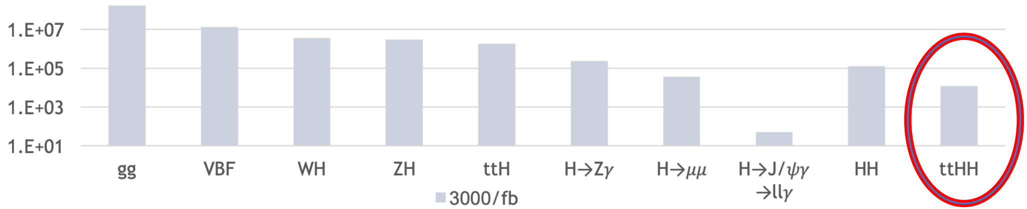
Current studies

Interest in this channel for HL-LHC and beyond:



- Benefit of larger statistics
- Sensitivity to Higgs self coupling and BSM searches

- C. Bautista, L. de Lima, R.D. Matheus, E. Ponton, L.A.F. do Prado, A. Savoy-Navarro, *Production of ttH and ttHH at the LHC in Composite Higgs Models.* P292-298: M. Cepeda et al., Report from the Working Group 2: *Higgs Physics at the HL-LHC and perspectives at HE-LHC*, arXiv: 1902.00134v2 [hep-ph].
- Lingfeng Lia , Ying-Ying Lib , and Tao Liub, *Anatomy of the tthh Physics at HL-LHC,* arXiv:1905.03772v1 [hep-ph].
- Shankha Banerjee, Frank Krauss, and Michael Spannowsky, *Revisiting the tthh channel at the FCC-hh,* arXiv:1904.07886v2 [hep-ph].
- Michelangelo L. Mangano, Giacomo Ortona, and Michele Selvaggi, *Measuring the Higgs self-coupling via Higgs-pair production at a 100 TeV pp collider,* arXiv:2004.03505v1 [hep-ph]

Signal Model for ttHH

- Goal: study ttHH independently of ttH

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i + \mathcal{O}(\Lambda^{-4}) + h.c.$$

- 6D gauge invariant operators that generate ttHH:

$$\left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$

$$g_{tth} \sim \frac{3\nu^2}{2\sqrt{2}}, \qquad g_{tthh} \sim \frac{3\nu}{2\sqrt{2}}$$

- 6D operator that generates ttHH also affects ttH

Signal Model for ttHH

- Would like a specific model to study the case where ttHH get modified while ttH is unchanged:

$$\Delta L \ \propto tth^2$$

- Creating a signal model containing 6D and 8D operators:

$$\mathcal{L} = \ \mathcal{L}_{SM} + \ \Delta\mathcal{L}$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \underline{G_1(H^\dagger H)(QHt^c + \text{h.c.})} + \underline{G_2(H^\dagger H)^2(QHt^c + \text{h.c.})}$$

$$G_1 \sim \frac{1}{M^2}, \qquad G_2 \sim \frac{1}{M^4}$$

Signal Model for ttHH

Modified m_t, ttH and ttHH coupling:

$$m_t = \frac{y_t v}{\sqrt{2}} + \frac{G_1 v^3}{2\sqrt{2}} + \frac{G_2 v^5}{4\sqrt{2}}$$

$$g_{tth} = \frac{y_t}{\sqrt{2}} + \frac{3G_1 v^2}{2\sqrt{2}} + \frac{5G_2 v^4}{4\sqrt{2}}$$

$$g_{tthh} = \frac{3G_1 v^2}{\sqrt{2}} + \frac{5G_2 v^4}{\sqrt{2}}$$

Requiring m_t and g_{tth} unchanged

$$G_1 = -G_2 v^2$$

$$y_t = \frac{\sqrt{2} m_t}{v} + \frac{G_2 v^4}{4}$$

$$g_{tthh} = \sqrt{2} G_2 v^4$$

$$\Delta\mathcal{L} = \frac{g_t}{2v} tthh = \frac{G_2 v^3}{\sqrt{2}} tthh$$

Simulation

Feynrules: creating a UFO model

Madgraph: importing the UFO model, generating pseudo data

Pythia: hadronization

Madanalysis: fastjet, making plots

- Madanalysis:

set main.fastsim.package = fastjet
set algorithm = antikt
set radius = 0.4
set ptmin = 5.0
set bjet_id.matching_dr = 0.4
set bjet_id.efficiency = 1.0
set bjet_id.misid_cjet = 0.0
set bjet_id.misid_ljet = 0.0

- Selections:

select (j) PT > 20
select (b) PT > 20
select (e) PT > 10
select (mu) PT > 10
select (j) ABSETA < 2.5
select (b) ABSETA < 2.5
select (e) ABSETA < 2.5
select (mu) ABSETA < 2.5

Check that ttH is unchanged

- Generate ttH at $\sqrt{s} = 13\ TeV$ at LO

SM:

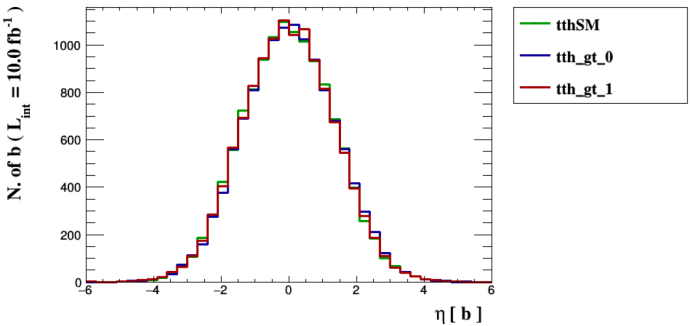
- $\sigma(t\bar{t}H) = 0.3987\ pb$

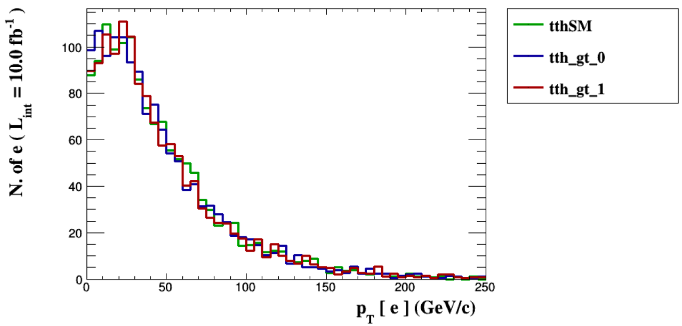
Signal model:

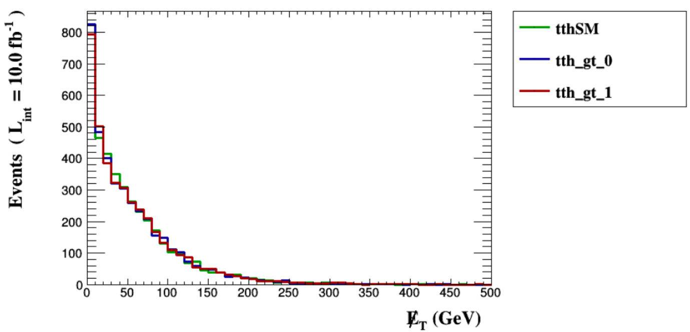
- $g_t = 0$: $\sigma(t\bar{t}H) = 0.4007\ pb$
- $g_t = 1$: $\sigma(t\bar{t}H) = 0.3988\ pb$

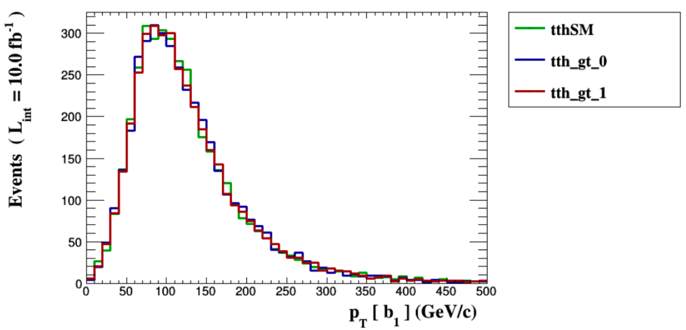
Check that ttH is unchanged

- Madanalysis/pythia:



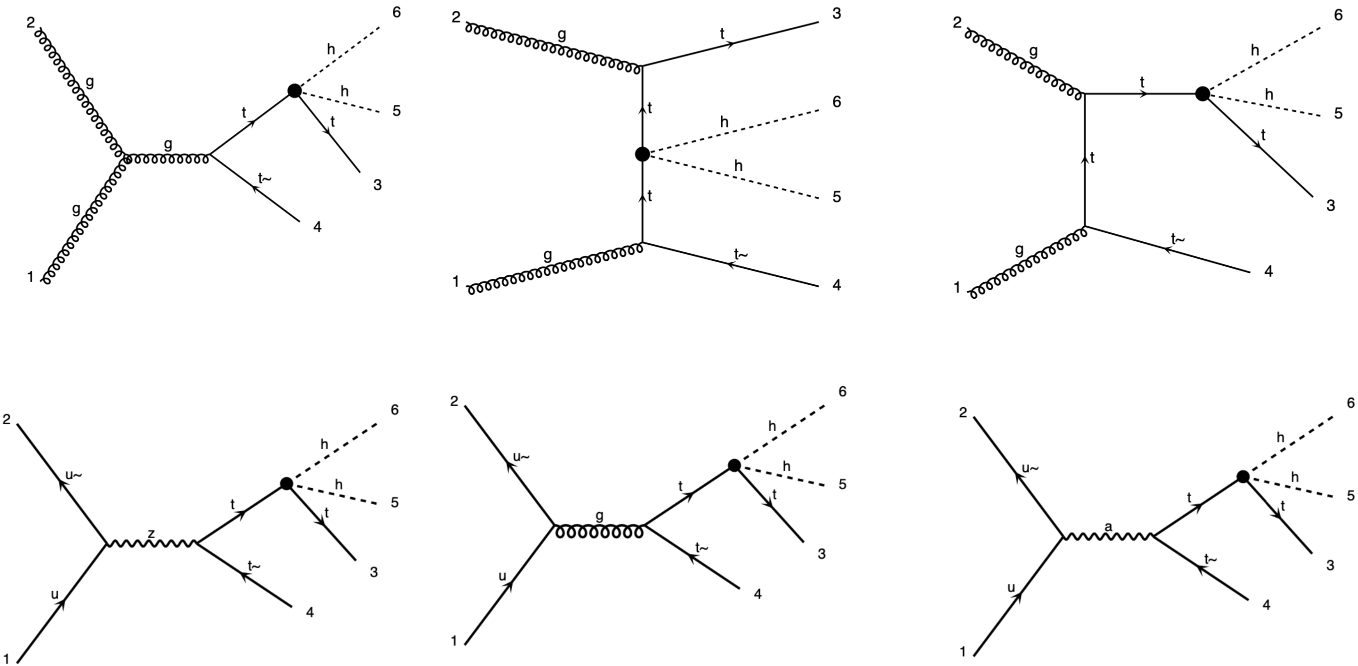






ttHH production

- Generate ttHH at $\sqrt{s} = 13\ TeV$ at LO
- Will switch to 14 TeV from now on
- Feynman diagrams for ttHH



ttHH production

SM:

- $\sigma(t\bar{t}HH) = 0.7494\ fb$

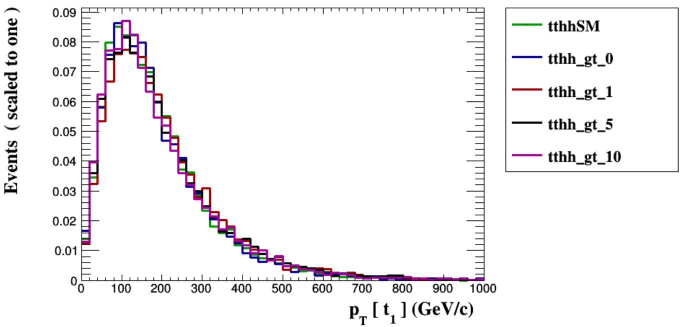
Signal model:

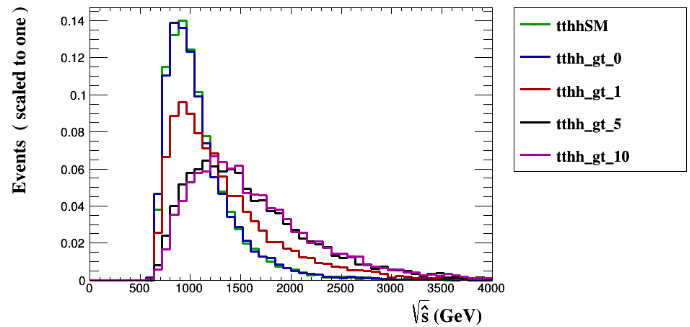
- $g_t = 0$: $\sigma(t\bar{t}HH) = 0.7387\ fb$
- $g_t = 1$: $\sigma(t\bar{t}HH) = 1.959\ fb$
- $g_t = 5$: $\sigma(t\bar{t}HH) = 20.91\ fb$
- $g_t = 10$: $\sigma(t\bar{t}HH) = 76.16\ fb$

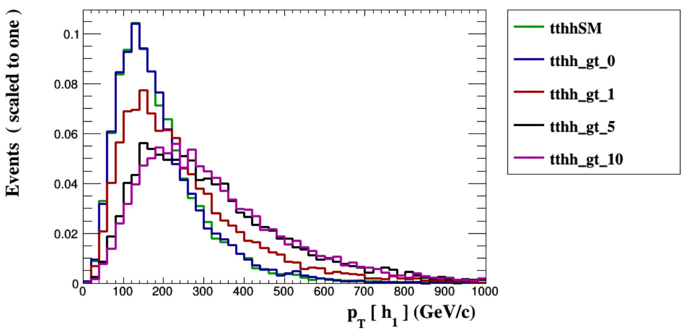
Focusing on
$g_t = 0$ and 1

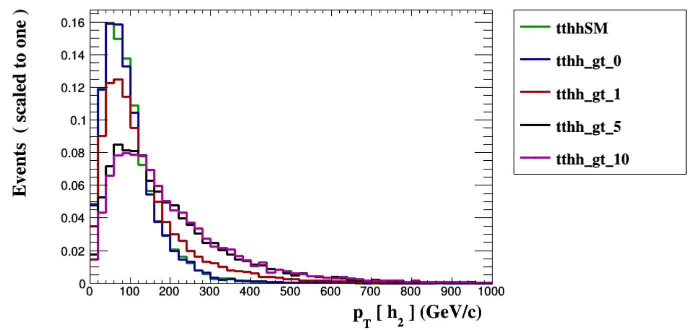
ttHH Kinematics

- Generator level plots (normalized to unity)



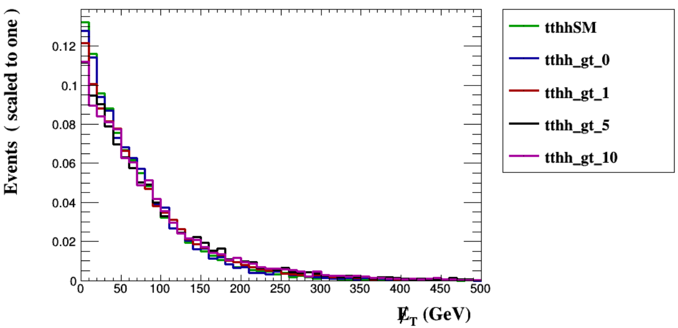


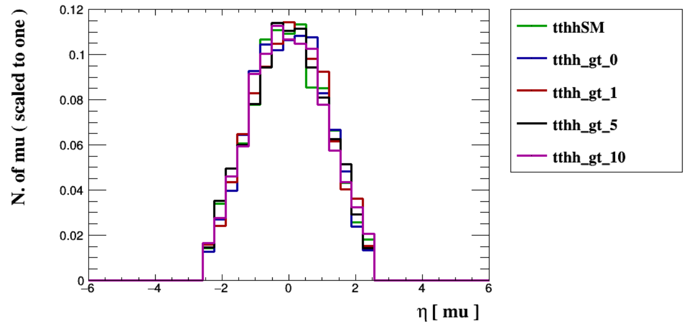


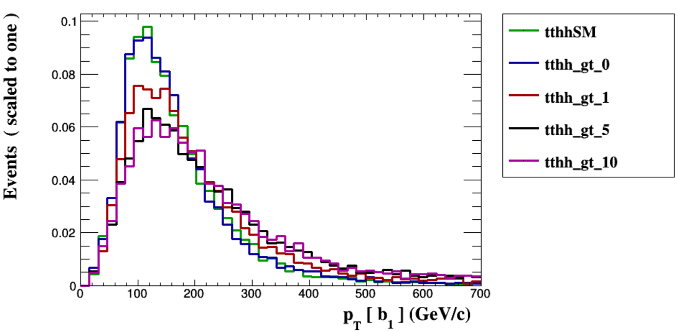


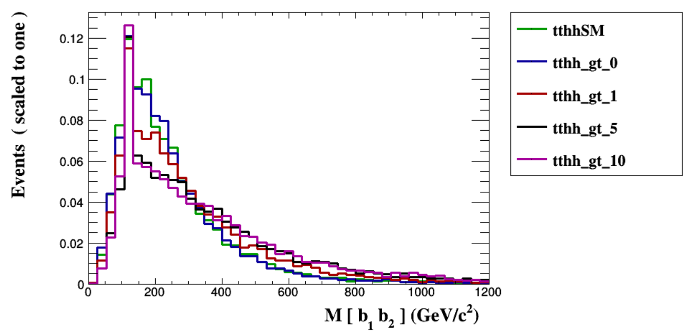
ttHH Kinematics

- Madanalysis/pythia (normalized to unity):









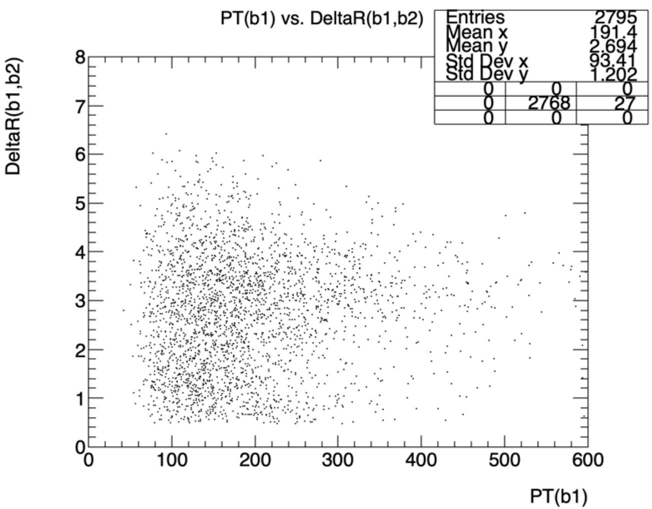
Delphes Detector Simulation

```
/===========================================================================\
| 1. Choose the shower/hadronization program     shower = Pythia8          |
| 2. Choose the detector simulation program    detector = Delphes          |
| 3. Choose an analysis package (plot/convert) analysis = MadAnalysis5     |
| 4. Decay onshell particles                    madspin = OFF              |
| 5. Add weights to events for new hypp.       reweight = OFF              |
\===========================================================================/
```

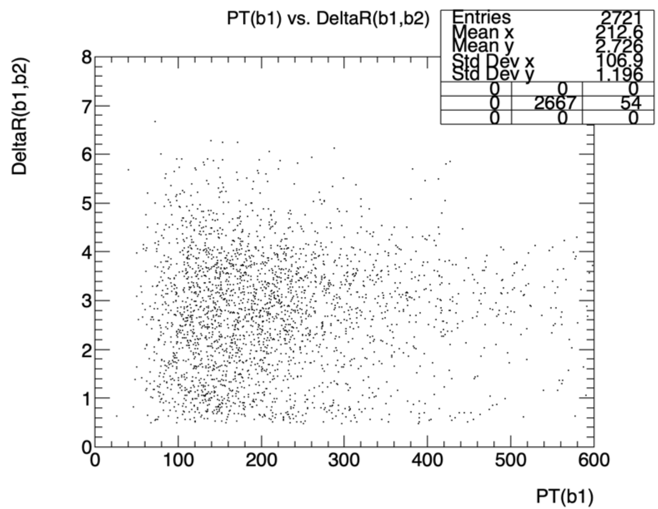
```
############
# Jet finder
############

module FastJetFinder FastJetFinder {
#   set InputArray Calorimeter/towers
  set InputArray EFlowMerger/eflow

  set OutputArray jets

  # algorithm: 1 CDFJetClu, 2 MidPoint,
3 SIScone, 4 kt, 5 Cambridge/Aachen, 6
antikt
  set JetAlgorithm 6
  set ParameterR 0.5

  set JetPTMin 20.0
}
```

Delphes Detector Simulation

- Signal model: more high PT b distributed at large DeltaR (b1,b2)
- Normalized to 10000 events



SM

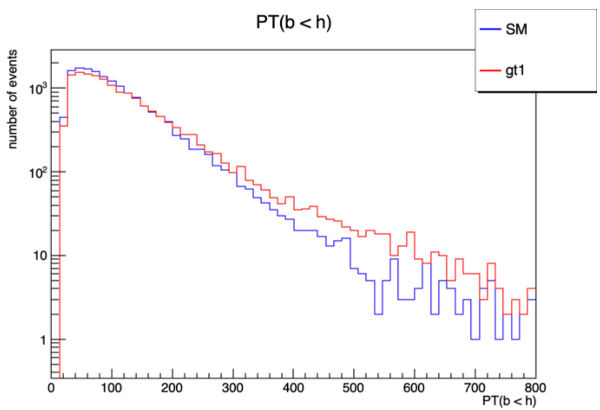


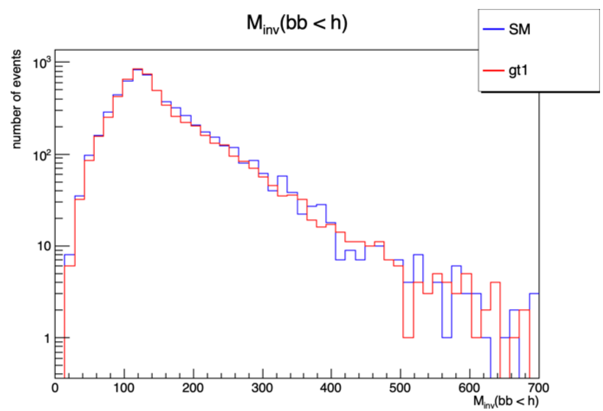
Signal model $g_t = 1$

Delphes Detector Simulation

- Matching b jets with gen particle based on truth information in Madgraph (Matching with DeltaR < 1, 0.7, 0.4)
- Plots are normalized to 10000 events

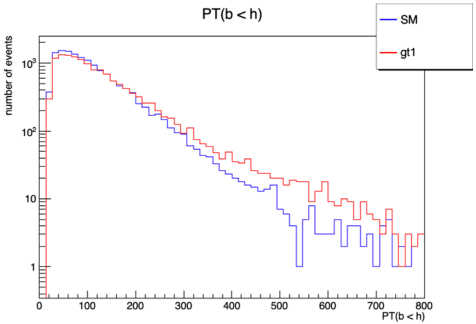
○ DeltaR < 1

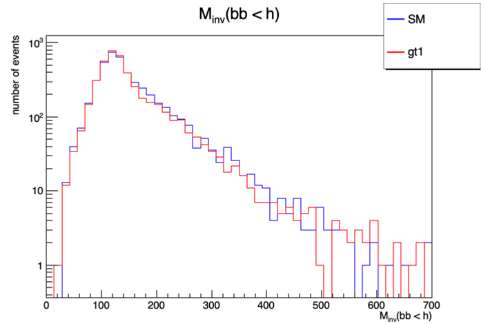




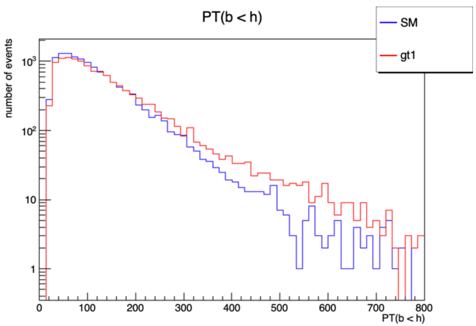
Delphes Detector Simulation

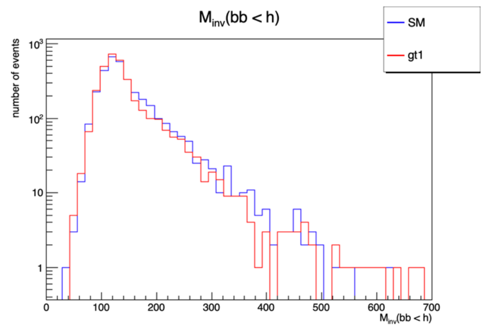
- DeltaR < 0.7





- DeltaR < 0.4

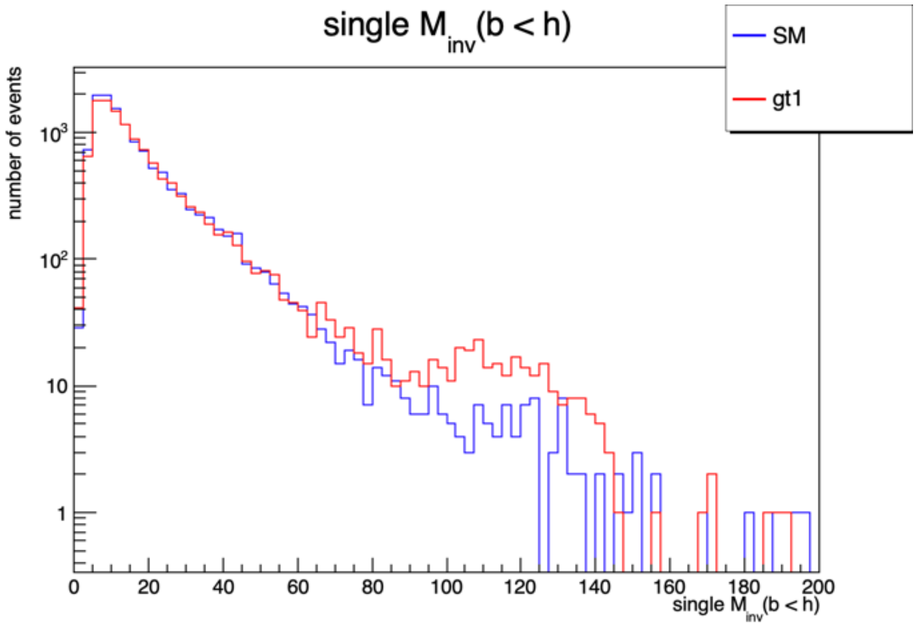




- Tighter matching leads to a sharper Higgs peak

Delphes Detector Simulation

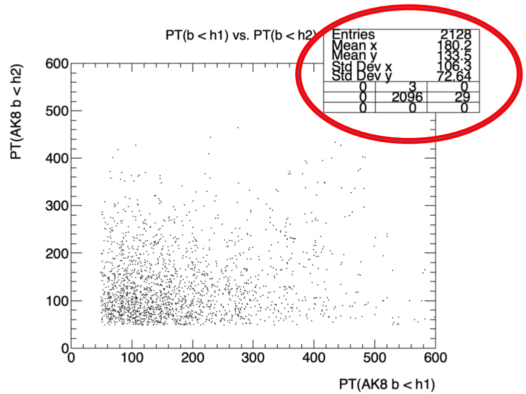
- Deviation from SM for single b jet mass:



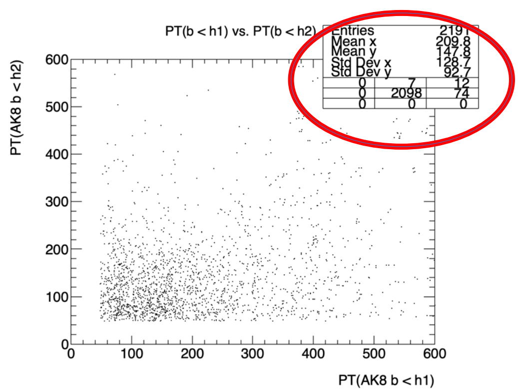
Focus on Boosted Higgs

- Highly boosted Higgs decaying to $b\bar{b}$
- Clustering into single b jet after detector simulation
- Looking at Fatjet

```
##################
# Fat Jet finder
##################

module FastJetFinder FatJetFinder {
  set InputArray EFlowMerger/eflow

  set OutputArray jets

  # algorithm: 1 CDFJetClu, 2 MidPoint, 3 SIScone,
4 kt, 5 Cambridge/Aachen, 6 antikt
  set JetAlgorithm 6
  set ParameterR 0.8

  set ComputeNsubjettiness 1
  set Beta 1.0
  set AxisMode 4

  set ComputeTrimming 1
  set RTrim 0.2
  set PtFracTrim 0.05

  set ComputePruning 1
  set ZcutPrun 0.1
  set RcutPrun 0.5
  set RPrun 0.8

  set ComputeSoftDrop 1
  set BetaSoftDrop 0.0
  set SymmetryCutSoftDrop 0.1
  set R0SoftDrop 0.8

  set JetPTMin 50.0
}
```



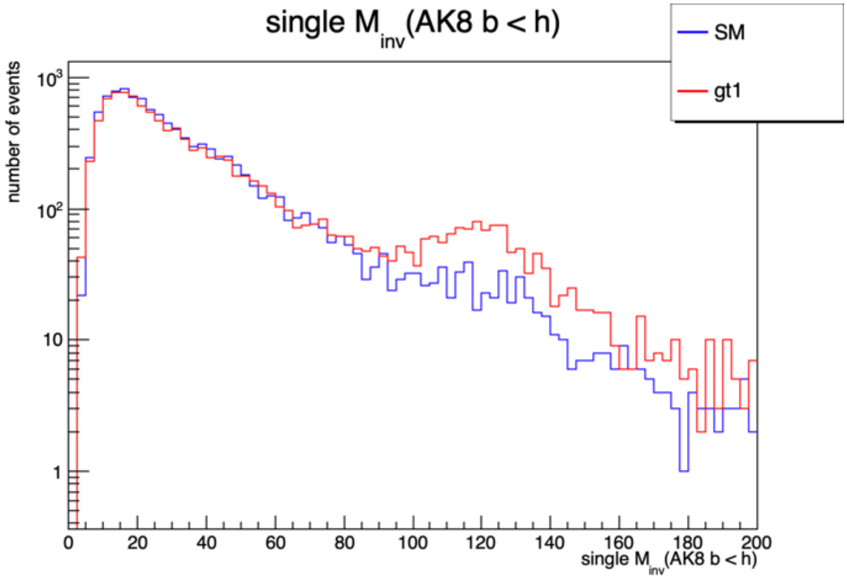
SM (DeltaR < 0.4)



$g_t = 1$ (DeltaR < 0.4)

Focus on Boosted Higgs

- Looking at Fatjet
- Invariant mass of single AK8 bjets



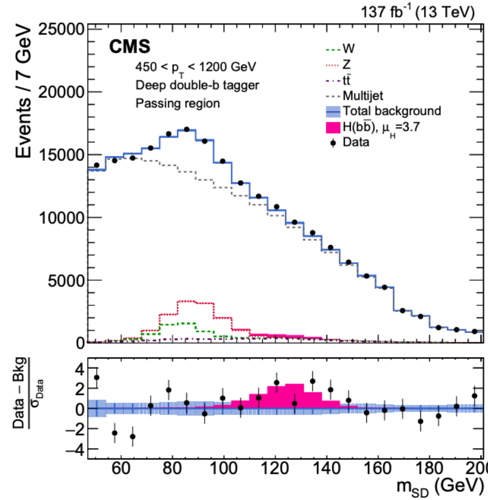
DeltaR < 0.4

Focus on Boosted Higgs

CMS-HIG-19-003

CERN-EP-2020-107
2020/06/25

Inclusive search for highly boosted Higgs bosons decaying to bottom quark-antiquark pairs in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$



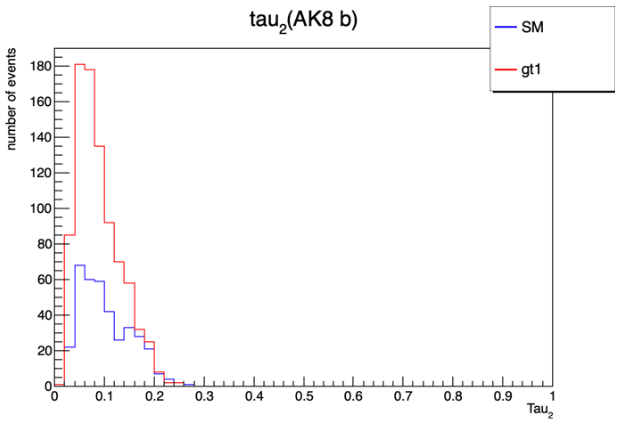
CMS search: Highly boosted Higgs to $b\bar{b}$ (2006.13251)

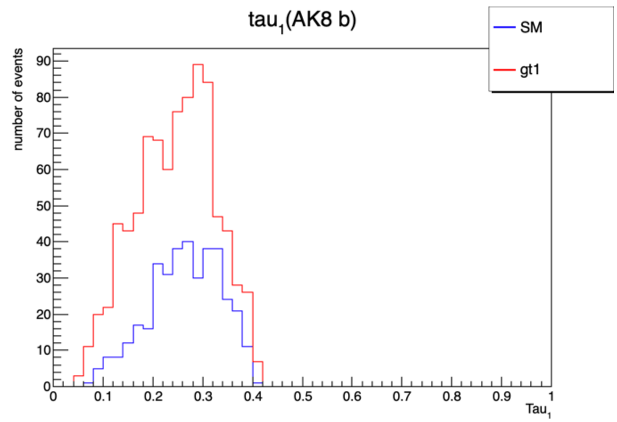
- Madgraph + Pythia (CUETP8M1 tune)
- Event reconstruction: particle-flow algorithm
- Soft-drop (SD) algorithm
- Deep double-b tagger
- Energy correlation functions

Focus on Boosted Higgs

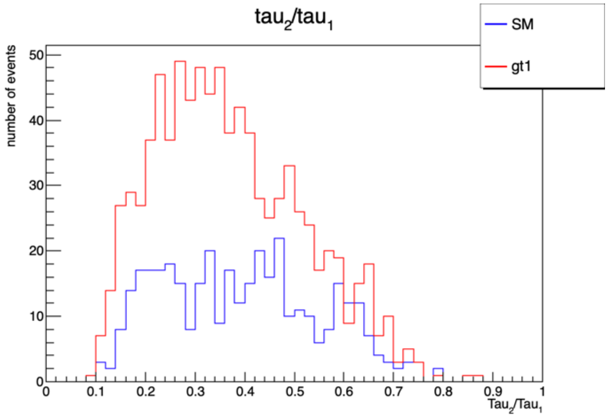
- Studying the jet substructure

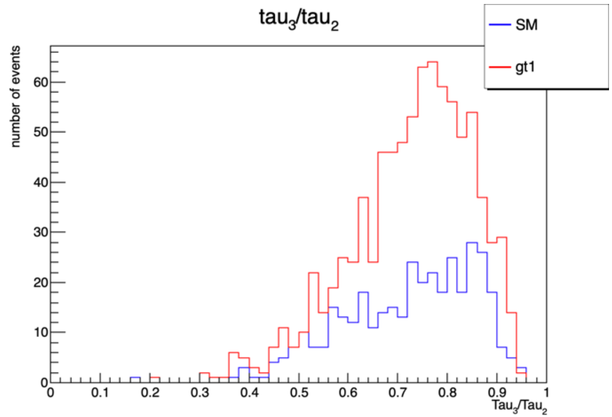
1. $Anti - k_T$ algorithm: AK8 jets
2. Soft-drop algorithm: angular exponent β = 0 and soft radiation fraction z = 0.1
3. ρ = 2 ln(mSD/pT), −6.0 < ρ < −2.1
4. 105 GeV < Minv(b) < 145 GeV, DeltaR < 0.4

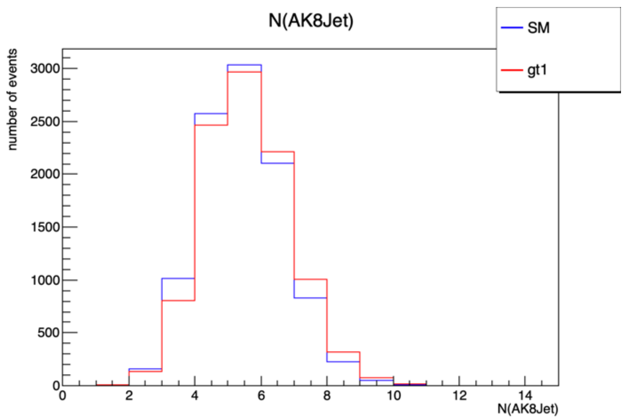




Focus on Boosted Higgs







Summary and Plans

Summary:

- A signal model to study ttHH independently of ttH
- Observe the enhancement of Higgs mass reconstruction for single b jets
- Focusing on boosted Higgs

Future plans:

- Run simulation at 14 TeV
- Switch into CMS analysis framework
- Apply Deep learning techniques such as double b tagger
- Investigate other jet substructure tools

THANKS

Backup

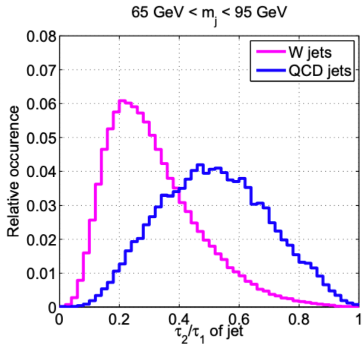
- N-subjettiness (arXiv:1011.2268[hep-ph])

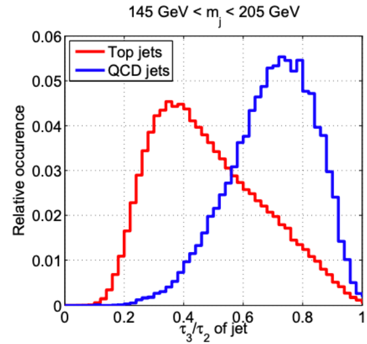
$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k} \min\{\Delta R_{1,k}, \Delta R_{2,k}, \cdots, \Delta R_{N,k}\}$$

$$\Delta R_{J,k} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

$$d_0 = \sum_k p_{T,k} R_0$$

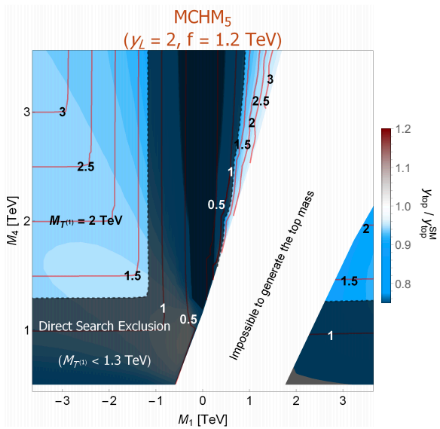
- Discriminating between boosted objects and QCD background.

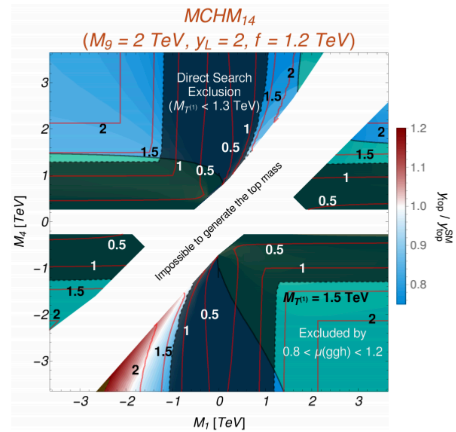


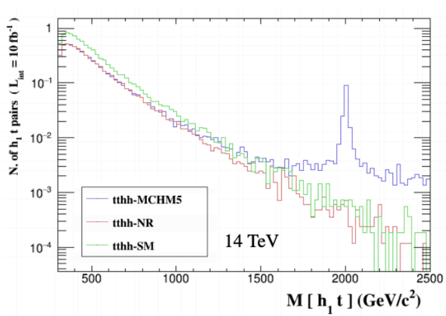


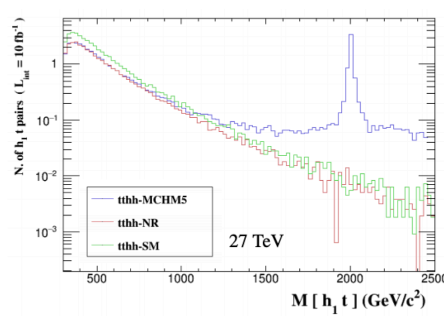
Backup

- C. Bautista, L. de Lima, R.D. Matheus, E. Ponton, L.A.F. do Prado, A. Savoy-Navarro, *Production of tth and ttHH at the LHC in Composite Higgs Models.*







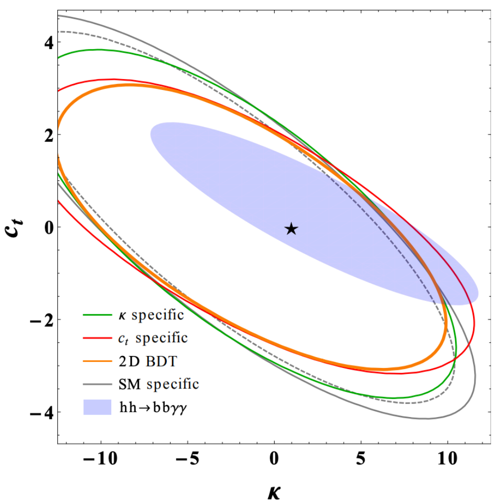


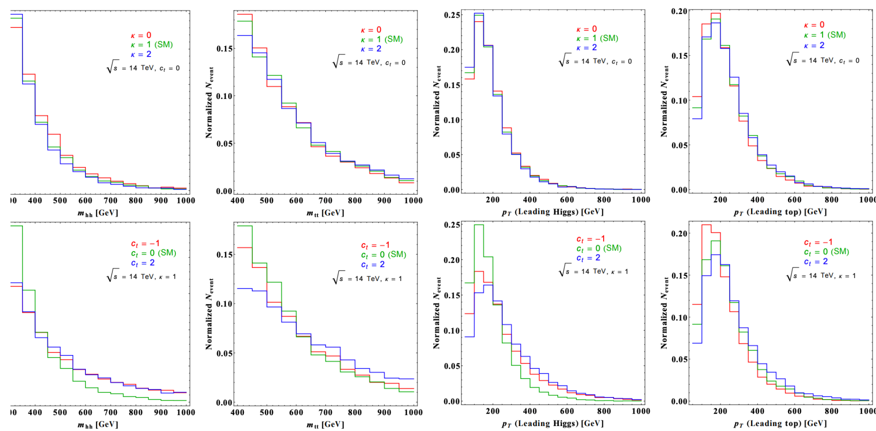
Backup

- Lingfeng Lia , Ying-Ying Lib , and Tao Liub, *Anatomy of the tthh Physics at HL-LHC,* arXiv:1905.03772v1 [hep-ph].

$$\mathcal{L} \supset -y\frac{m_t}{v}t\bar{t}h - \kappa\frac{1}{3!}\frac{3m_h^2}{v}h^3 - c_t\frac{1}{2!}\frac{m_t}{v^2}t\bar{t}hh$$

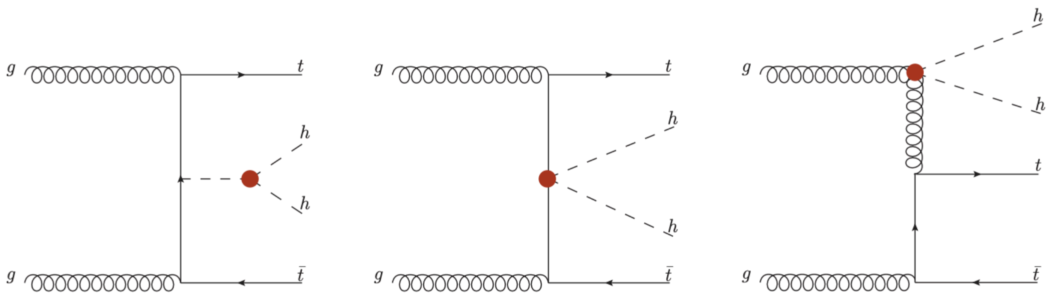
$$\kappa \equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM}}} \qquad\qquad y \equiv \frac{y_{tth}}{y_{tth}^{\mathrm{SM}}}$$





Backup

- Shankha Banerjee, Frank Krauss, and Michael Spannowsky, *Revisiting the tthh channel at the FCC-hh,* arXiv:1904.07886v2 [hep-ph].



$$\mathcal{L}^{\mathrm{simp}} = \mathcal{L}^{SM} + (1-\kappa_\lambda)\lambda_{\mathrm{SM}} h^3 + \kappa_{t\bar{t}hh}(\bar{t}_L t_R h^2 + \mathrm{h.c.}) - \frac{1}{8}\kappa_{\mathrm{gghh}} \mathrm{G}^{\mathrm{a}}_{\mu\nu}\mathrm{G}^{\mu\nu}_{\mathrm{a}}\mathrm{h}^2$$

- 68% (95%) confidence level:

$$-0.53\ \mathrm{TeV}^{-1} < \kappa_{t\bar{t}hh} < 0.89\ \mathrm{TeV}^{-1}\ (-0.81\ \mathrm{TeV}^{-1} < \kappa_{t\bar{t}hh} < 1.17\ \mathrm{TeV}^{-1})\quad 3/\mathrm{ab}$$
$$-0.25\ \mathrm{TeV}^{-1} < \kappa_{t\bar{t}hh} < 0.61\ \mathrm{TeV}^{-1}\ (-0.39\ \mathrm{TeV}^{-1} < \kappa_{t\bar{t}hh} < 0.75\ \mathrm{TeV}^{-1})\quad 30/\mathrm{ab}.$$

$$-3.09 < \kappa_\lambda < 2.44\ (-3.60 < \kappa_\lambda < 3.16)\quad 3/\mathrm{ab}$$
$$-2.56 < \kappa_\lambda < 1.64\ (-2.83 < \kappa_\lambda < 2.06)\quad 30/\mathrm{ab}$$